Novel designs for improving the performance of hollow fiber membrane distillation modules

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Abstract

Five types of novel hollow fiber module configurations with structured-straight fibers, curly fibers, central-tubing for feeding, spacer-wrapped and spacer-knitted fibers, have been designed and constructed for the Direct Contact Membrane Distillation (DCMD) process. Their module performances were evaluated based on permeation flux experiments, fluid dynamics studies, and tracer-response tests for flow distribution as well as process heat transfer analysis.

The novel designs showed flux enhancement from 53% to 92% compared to the conventional module, and the spacer-knitted module had the best performance. The fluxes of all the modified configurations, except the structured-straight module, were independent of the feed flow velocity, and the modules with undulating membrane surfaces (curly and spacer-knitted fibers) were able to achieve more than 300% flux improvement in the laminar flow regime. The improved performance was attributed to the improved fiber geometries or arrangements that can provide effective boundary layer surface renewal and more uniform flow distribution, confirmed by the sodium chloride tracer response measurements. The heat transfer analysis underscores the advantage of the module with curly fibers with the least temperature polarization effect (temperature polarization coefficient =0.81−0.65 at $T_m = 303 - 333\text{K}$), which is favorable for enhancing permeation flux.

Keywords: hollow fibers, module design, temperature polarization, membrane distillation

I. Introduction

Membrane distillation (MD) is a process for water treatment that is driven by a temperature gradient across a microporous hydrophobic membrane between a hot feed solution and a cold permeate. It involves both mass- and heat-transfer processes: the evaporation of the water molecules at the hot interface, the transport of water vapor across the porous partition (the membrane) and the condensation of water vapor at the cold interface [1]. MD is a promising technique for water desalination because of several advantages: low sensitivity to salt concentration and theoretically 100% salt rejection; feasibility to utilize low-grade heat and renewable energy (e.g., waste heat or solar power); low vulnerability to membrane fouling and good performance under mild operating conditions as compared to conventional, multi-stage distillation or reverse osmosis (RO) [2, 3]. Direct contact membrane distillation (DCMD) is the most studied and simplest mode among the various MD processes because no external condenser is required as compared to vacuum membrane distillation (VMD) and sweep gas membrane distillation (SGMD) [2, 4-6].

Despite many attractive characteristics and many lab-scale studies, MD has not been widely implemented in industry [3, 7]. Major challenges impeding its application include the following: developing appropriate MD membranes to avoid pore wetting; increasing the permeation rates; assessing the energy consumption; and mitigating flow maldistribution and/or poor hydrodynamics and severe temperature polarization (TP) that compromise module performance [2]. In recent years a surge of studies have focused on membrane development [8-12] and energy analysis [7, 13-16]. However, there has not been a comprehensive investigation of MD module design. Yet the potential benefits of improved module design indicate that a more intensive effort is needed in this area.

Thus far most of the work on hydrodynamic improvement in MD studies has focused on flat sheet membrane modules that have small membrane areas and thus are limited to laboratory research [5, 17-20]. In industry, hollow fiber-based membrane modules are preferable due to their larger membrane area per unit volume and reduced vulnerability to TP [1]. Although it has been often stated that poorly-designed hollow fiber modules will result in reduced productivity, increased energy consumption and shortened membrane lifespan [21], there are limited studies on improving fluid dynamics and designing hollow fiber modules for MD applications in the open literature [3, 22-25]. It is well-recognized that by incorporating proper flow alteration aids or modifying fiber geometries to create secondary flows or eddies (such as novel fiber configurations or turbulence promoters, e.g. spacers or baffles), the permeation flux can be enhanced and TP can be mitigated. An early exploration on hollow fiber module design by Schneider *et al.* [25] in 1988 investigated the effects of module size and modified fiber geometries on the transmembrane flux of the DCMD process. It showed that larger modules could achieve uniform flow more easily than smaller ones and certain capillary arrangements (twisted and braided geometries) could lead to much higher fluxes than those with straight woven fabric designs. In 2008 Teoh et al. [24] studied different hollow fiber configurations in the DCMD process and found that the introduction of baffles could increase the feed-side heat-transfer coefficients leading to 20−28% flux enhancement. In addition, they also explored the concepts of wavy geometries (twisted and braided) of hollow fibers that were able to achieve as high as a 36% flux enhancement compared to the unaltered conventional modules. Recently, Yang et al. [12] described strategies to improve PVDF-based module performance in the DCMD process that included the investigations on the module size, packing density and critical fiber length combined with heat-transfer analysis. Although the existence of simultaneous concentration polarization (CP) and TP will lead to the reduction of mass and heat transfer driving forces, it is well-established that the effect of CP in the DCMD system is negligible in comparison to that of TP [26, 27]. Therefore, the quantification of the TP effect, which is used to assess the thermal efficiency, is essential for the implementation of an MD system [1, 8, 26]. Yet, none of the above-mentioned MD module studies have addressed associated conductive heat loss or the mitigation of TP by altering the fiber geometries or introducing turbulence aids.

In spite of the absence of comprehensive module design work for MD applications, numerous prior studies have been done for general gas-liquid/ liquid-liquid contactors with focuses on the introduction of turbulence promoters (baffles/spacers/channel designs) or special housing configurations as well as on various aspects related to packing density, flow uniformity and shell-side hydrodynamics [21, 28-33]. These studies concluded that non-ideal flow distribution in a module will lead to less active membrane area, insufficient mixing and local loss of driving force, and hence low heat- or mass-transfer efficiencies. A recent review by Yang et al. [21] summarized the most practical membrane module design concepts and dynamic shear-inducing techniques to enhance liquid separation by hollow fiber modules. Unfortunately, very few of these design concepts have been adapted to MD applications.

Moreover, no report was found to correlate the flow distribution with MD process enhancement. In the DCMD process employing shell-side feed, the occurrence of significant channeling, bypassing, or dead zones can greatly reduce the local driving force and decrease the module performance. Hence, the detection of the flow distribution at the shell-side is important for module design. There are two main methods for characterizing the flow distribution: the experimental approach (tracer response technique) and mathematical modeling [22, 31, 34]. The tracer technique is widely applied for the characterization of the flow distribution and the degree of mixing in membrane bioreactors as well as for the visualization of the shell-side flow distribution in randomly packed membrane contactors [31, 35, 36]. It provides the residence-time distribution (RTD) for the fluid in a closed vessel [37]. However, no comprehensive RTD study has been done to evaluate MD module performance.

Therefore, this study attempts to develop novel hollow fiber module designs that can improve hydrodynamics and thus the MD module performance. The following issues will be addressed: (1) novel hollow fiber module design; (2) performance evaluation of various designs based on flux enhancement; (3) hydrodynamic studies of modified modules; (3) applications of tracer-response measurement for module flow distribution; (4) heat-transfer analysis to quantify the TP effect and conductive heat loss of different design configurations.

2. Experimental

2.1 *Hollow fiber module fabrication & assembly procedure*

Polyvinylidene fluoride (PVDF) hollow fiber membranes developed by a commercial supplier were used to fabricate lab-scale MD modules. The fibers were potted into the housings that are made by transparent Acrylic material, which is provided by local supplier **Acefund Pte Ltd**., to facilitate direct observation of the flow conditions around the fiber bundles. Various module configurations were assembled in different ways with similar specifications (Table 1): inner diameter 19 mm and effective length 450 mm; packing density of 30%; and membrane area of 0.1−0.11 m^2. In this study a randomly packed module, which contained 51 randomly packed fibers, was fabricated and used as the conventional module benchmark. The fabrication procedure can be found in our previous work [12]. In the module fabrication process, care must be taken to avoid damaging the membrane surface and no metal parts were inserted.

Five novel designs were compared. First, a special module with structured-straight fibers was fabricated by weaving all fibers into a fabric sheet that was subsequently rolled up and packed into the housing (Fig. 1a). This structured array is anticipated to avoid the clustering of hollow fibers and could possibly lead to more uniform flow distribution in the shell-side.

The second module contains curly fibers (Fig. 1b). To create a curly fiber geometry, an appropriate temperature and heat-treatment duration as well as a certain winding angle of the curl were selected. The fibers were first rolled up around stainless steel rods (diameter 1.6 mm) with a winding angle of 60° and then placed in an oven at 60°C for 1hr until the curly shape was permanently established. This configuration is expected to create an undulating membrane surface that will help to change the flow geometry which might lead to enhanced hydrodynamics and surface renewal under laminar flow conditions. To characterize this configuration the major design variable is the winding angle.

To create transverse flow and more uniform fiber arrangement in a module, a central tube was inserted and surrounded by the woven fabric sheet in the third design; the feed inlet and outlet were still located at the shell-side via two drawtubes mounted on the central tube (see Fig. 1c). The gaps between the drawtubes and the feed entrance or exit on the housing were sealed using epoxy (Araldite®) ; in this case the feed would mostly flow through the holes on the central tube and the permeate would flow through the fiber lumen. Caution must be taken when designing the interval and number of holes on the central tube, because it is related to the uniformity of the flow distribution through the holes and the degree of transverse flow pattern. To investigate the potential variations of this configuration, the design of the central tube can be varied by adjusting the shapes of the flow distributing holes and the intervals between holes. In addition, the tube size, wall-thickness, size/shape of the holes and interval between the holes should be appropriately chosen.

The fourth design with spacer-wrapped fibers is shown in Fig. 1d. Here the woven fabric sheet was wrapped by spacers (with mesh size 1.6 mm) and rolled up. This is expected to create transverse flow across the membrane surface by evenly allocating layers of spacers between layers of fibers. However, it is possible that the inappropriate allocation of spacers or a tightly packed pattern might lead to liquid stagnation that instead would adversely affect the hydrodynamics.

In the fifth novel design that fibers were knitted into the mesh of the spacer (refer to the spacer-knitted module in Fig. 1e) to facilitate a meandering fluid flow. The inappropriate allocation of spacers or over-packed pattern can also lead to adverse effects on the hydrodynamics due to the liquid stagnation between the mesh and fibers as observed with the spacer-wrapped fibers.

2.2 Module performance evaluation and heat transfer analysis

To evaluate the module performance for various configurations, the following experiments were carried out: (i) attainable flux experiments in which the feed temperature was varied while holding the permeate temperature and other operating conditions constant; (ii) fluid dynamics experiments in which the recirculating feed or permeate velocity was varied while holding the other operating conditions constant. All the experiments were conducted using the DCMD system. The experimental setup is shown in our previous work [12]. Both the feed and permeate solutions were cycled through the hollow fiber module in countercurrent mode. For the performance tests using synthetic seawater (3.5 wt% sodium chloride solution), the operating details can be found in the literature [12].

Deionized (DI) water was also used in the experiments to investigate the TP effect associated with the heat transfer analysis while excluding the CP effect. Both hot and cold DI water streams were circulated countercurrently through the shell and lumen sides. On the shell side the hot water was heated to between 308 K–343 K and circulated by a peristaltic pump (1–5.6 $L \cdot min^{-1}$). On the lumen side the cold permeate was cooled by a circulating bath (between 298 K–328 K) and cycled by another peristaltic pump (0.1-2.1 $L \cdot min^{-1}$). Two conductivity meters were installed to assess the water quality in the feed and permeate sides, respectively. The product was collected in an overflow tank placed on a balance (±0.1 g). The fluid dynamics experiments were performed with careful control of the temperature difference (<10 K) between the hot feed and cold permeate.

2.3 *Tracer response protocol*

The tracer-response studies were conducted using the same DCMD set-up to investigate the shell-side flow distribution in these modules. A schematic showing a module with the location of tracer injection and effluent concentration monitors is depicted in Fig. 2. At room temperature DI water was pumped into the shell-side of the modules as the feed stream (blank background solution) and a pulse input of sodium chloride solution was injected at the feed inlet. The tracer response signal was measured at the exit of the effluent stream. Since the salt rejection of this PVDF-based hollow fiber membrane is 100% [12], no leakage of the tracer was detected on the lumen side. The amount of tracer used was 1 mL with a concentration of 1 $mol \cdot L^{-1}$. The resulting concentration of tracer at different times was monitored by a conductivity meter (±0.1 $\mu s \cdot cm^{-1}$) installed at the exit of the effluent. The signals were monitored and recorded via a data-acquisition system. To determine the relationship between the concentration of sodium chloride solution and corresponding conductivity, samples of known concentrations were tested to obtain conductivity values using an external conductivity bridge.

In this experiment the proper selection and use of the tracer are essential to get correct *E(t)* curves that represent the age distribution of all components in the effluent stream. A physical, nonreactive and unabsorbable chemical must be used as a tracer. A sodium chloride solution meets these criteria and was therefore chosen in this study. The concentration and dosage of the tracer solution also affect the results, and many attempts were made to determine the appropriate concentration and dosage to detect the shell-side flow distribution in the modules. In addition, the pumping speed had to be carefully chosen due to the relatively small size of the test modules. The feed solution (pure water) was pumped at 2.1−2.4 $L \cdot min^{-1}$ into the shell-side until the effluent had no recorded tracer. To obtain reproducible and comparable results, the tracer tests for each module were repeated 8−10 times under constant operating conditions.

2.4 Error assessment

All the above-mentioned experiments were repeated and showed reproducible results.

The results for the water-flux fluctuation were within ±5% (illustrated as error bars in the figures). The conductivity meters had accuracies of ±0.1 ms·cm^{-1}(feed side) and ±0.1 μs·cm^{-1} (permeate side), respectively. Two modules for each configuration were fabricated by following the same procedures and measured repeatedly under the same operating conditions. The temperature and flow rate variations were strictly controlled within ±0.4°C and ±0.2 L·min^{-1}, respectively. These would also result in less flux fluctuation.

3. Theoretical basis for data analysis

3.1 Temperature polarization coefficient and heat loss analysis

This study focuses on the application of an experimental approach to quantify the TP effect and acquire the temperature polarization coefficient (TPC). The following modeling considerations (assumptions) are applied:

(a) Theoretically, the vapor flux N can be expressed in terms of the transmembrane temperature difference when it is less than 10°C and pure water is used as feed [1]:

$$N = C \frac{dP}{dT}\Big|_{T_m} \left(T_{fm} - T_{pm}\right) \tag{1}$$

where C is the mass-transfer coefficient, T_m is the membrane temperature, T_{fm} and T_{pm} are the membrane surface temperatures on the feed and the permeate sides, respectively. By assuming the temperature polarization effect is similar on both sides of the membrane, T_m can be estimated by $(T_f + T_p)/2$.

(b) The Clausius-Clapeyron equation is applicable to determine the vapor pressure gradient dP/dT across the membrane when assumption 1) is satisfied. Hence,

$$\frac{dP}{dT}\Big|_{Tm} = \frac{P\lambda M}{RT^2}\Big|_{Tm} \tag{2}$$

where λ (J·kg^{-1}) is the latent heat-of-vaporization, *M* is the molecular weight of water, *R* is the gas constant (8.314 J·K^{-1}), and P is obtained from the Antoine equation [38].

The overall heat-transfer flux in MD, q, consists of the conductive heat flux q_c across the membrane and the latent heat transfer q_v accompanying the vapor flux *N* [1]:

$$q = q_c + q_v = \left(\frac{k_m}{\delta_m}\right)\left(T_{fm} - T_{pm}\right) + N\gamma = \left(\frac{k_m}{\delta_m} + \gamma \cdot C\frac{dP}{dT}\Big|_{Tm}\right)\left(T_{fm} - T_{pm}\right) = H\left(T_{fm} - T_{pm}\right) \tag{3}$$

where H is the effective heat-transfer coefficient based on the transmembrane temperature difference, δ_m is the wall thickness of the membrane, and k_m (W·m^{-1}·K^{-1}) is the overall thermal conductivity of the membrane. The k_m/δ_m value of the PVDF fiber used in this study is taken as 274 W·m^{-2}·K^{-1} based on the method provided by Sarti et al. [39]. Combining Eq. (3) with the energy-conservation Eq. (4), TP can be determined quantitatively by Eq. (5):

$$q = h_f\left(T_f - T_{fm}\right) = h_p\left(T_p - T_{pm}\right) \tag{4}$$

$$\left(T_{fm} - T_{pm}\right) = \left(T_f - T_p\right)\Big/\left(1 + H/h_f + H/h_p\right) = \tau\left(T_f - T_p\right) \tag{5}$$

where h_f and h_p are the local heat-transfer coefficients for the hot feed and the cold permeate sides, respectively. $\tau = 1\Big/\left(1 + H/h_f + H/h_p\right)$ is the TPC that represents the contribution of the overall thermal driving force $\left(T_f - T_p\right)$ to the effective mass-transfer driving force $\left(T_{fm} - T_{pm}\right)$. The schematic of the temperature and the vapor-pressure profiles in the MD process is given in Fig. 3. Combining Eqs. (3) and (5) yields the following:

$$\frac{\Delta T}{N\gamma} = \frac{1}{dP/dT}\frac{1}{\gamma C}\left(1+\frac{k_m/\delta_m}{h}\right)+\frac{1}{h} \tag{6}$$

where $h \equiv 1/\left(1/h_f + 1/h_p\right)$ is the overall boundary layer heat-transfer coefficient and $\Delta T = \left(T_f - T_p\right)$. Therefore, with the measurable quantities k_m/δ_m, T_f, T_p and N as well as the predetermined values of dP/dT from Eq (2), the only unknown parameters h and C can be calculated from the intercept and the slope by plotting $\frac{\Delta T}{N\lambda}$ versus $\frac{1}{dP/dT}$ as explained by Schofield *et al.* [1].

3.2 Residence-time distribution (RTD)

This current study will use the sodium chloride tracer-response technique [37] for investigating the flow distribution on the shell-side of novel hollow fiber configurations. An example of an initial tracer concentration c (mol·m^{-3}) and its corresponding temporal values in the effluent stream known as *C(t)* curve for pulse injection is shown in Fig. 4. The RTD function *E(t)* (s^{-1}) can be used to further interpret the residence-time results [37]:

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t)dt} \tag{7}$$

where the denominator represents the dosage of the tracer injected at the feed entrance; it is also the area under the *C(t)* curve.

In the RTD approach many metrics can be used to evaluate the results. One of the main parameters is the mean residence time (t_m, s) that can be calculated based on the *E(t)* curve:

$$t_m = \int_0^\infty tE(t)dt \tag{8}$$

The theoretical (plug flow) residence time $\bar{t}$ (s), which is also as known as hydraulic residence time, is equal to the actual vessel volume V divided by the fluid flow rate Q_0. In a hollow fiber MD module the difference between $\bar{t}$ and t_m shows the degree of mixing in the vessel [37], i.e., a larger deviation might indicate a longer contact time and hence more effective heat transferred across the membrane. However, the uniformity of the flow distribution is also crucial in the vessel design. Thus, another important parameter is used to represent the spread of the RTD curve − the variance σ^2; a larger value indicates a wider spread, or more deviation from the uniform flow pattern [37].

$$\sigma^2 = \int_0^\infty \left(t - t_m\right)^2 E(t)dt \tag{9}$$

In order to obtain comparable results for vessels of different size and mean residence time, the normalized *E(t)* function and dimensionless form of variance are more commonly used:

$$E_\theta(\theta) = t_m E(t) \tag{10}$$

$${\sigma_\theta}^2 = \int_0^\infty \left(\theta - 1\right)^2 E_\theta\left(\theta\right) d\theta = \frac{\sigma^2}{{t_m}^2} \tag{11}$$

By applying the above RTD theory with the experimentally measured parameters (e.g., the tracer entrance concentration C_0 and dosage of tracer injected) and a responding concentration curve $C(t)$ that can be obtained from the assessment of tracer concentration in the effluent stream, the RTD function curve $E(t)$ can be determined based on Eq. (7). Thus, the mean residence time t_m and variance σ^2 (as well as the dimensionless variance) can be calculated based on Eqs. (8) to (11), respectively.

4. Results and discussion

4.1 Membrane properties

As mentioned previously, a newly-developed PVDF hollow fiber membrane was characterized and tested in the current study; its properties are given in Table 1. It can be seen that this highly porous PVDF fiber showed reasonably large contact angles for water, high liquid-entry pressure for water (LEPw), good mechanical strength, small maximum pore size and a narrow pore-size distribution. More information on the methodologies for membrane characterization can be found in our previous work [12].

4.2 Attainable flux (feed-temperature tests)

Fig. 5 plots the permeation flux as a function of feed temperature for six module configurations. All five modified modules show improved performance over the conventional randomly packed module. The greatest enhancement is achieved by the modules with spacer-knitted and curly fibers for which the flux is increased more than 90% at T_f =313 K and 70% at T_f =333 K, respectively. The modules with curly fibers and spacer-wrapped fibers show similar performance, while those with central tubing and straight fibers are slightly lower, but still show significant improvement over the randomly packed module. Teoh et al. [24] reported that the maximum flux enhancement achieved in modules with spacers/baffles or wavy geometries was only from 20 to 36% at feed temperature T_f =348 K. In comparison, the 70 to 90% improvement under milder operating temperature in this study is encouraging, and may be due to more appropriate choice of flow rates.

The enhancement of permeation flux in the modified modules would be due to the improved hydrodynamic conditions achieved by the modified shell-side flow channels in the novel configurations. Hence, it is anticipated that the heat and mass transfer would increase and the TP effect would decrease in a well-designed module when compared to the conventional randomly packed configuration. The discussion in the following sections addresses these points. In addition, another important factor that could affect the heat- and mass-transfer processes is fluid channeling or bypassing (shell-side) that was characterized using the tracer-response technique and will be discussed later.

4.3 Fluid dynamics

Experiments were performed to study the effects of the recirculating flow velocities (characterized as Reynolds number, Re, of the feed and permeate) on the fluxes in different membrane modules. Fig. 6 shows the permeation flux as a function of the Re_f of the feed flow for six different modules. Four of these novel designs show relatively stable fluxes in the range of 10 to 12 $kg \cdot m^{-2} \cdot h^{-1}$ from extremely low Re_f (laminar condition, e.g., $Re_f < 500$) to turbulent conditions ($Re_f > 2000$). This represents a significant improvement over the conventional randomly packed module as well as the structured-straight module, whose flux initially was rather low and increased with increasing Re_f until turbulent flow occurred. It is well understood that the steady flux across the Re range indicates a shift to the heat and mass transfer being controlled by the membrane and/or the lumen-side boundary layer. Normally, a higher recirculating velocity (i.e., higher mixing intensity) can help to reduce the thickness of the boundary layer adjacent to membrane surface and maximize the driving force between the feed and permeate sides [14, 40, 41], which is favorable for the mitigation of concentration and temperature polarizations. However, increased pumping energy is required to provide a higher velocity. From this study it can be seen that a much lower velocity can be chosen by employing novel configurations to reach the steady flux. Hence, there is no need to increase the flow rate.

From Fig. 6 it can also be observed that when compared with the randomly packed module, a one to three-fold flux enhancement could be obtained even at an extremely low flow velocity in four modified configurations. The highest flux enhancement (>300 %) was achieved by the modules with undulating membrane surface (spacer-knitted and curly fibers) under a low operating flow rate range. This might be due to a more even flow distribution in the modified module that improves the fluid dynamics. This finding will be corroborated by conducting residence-time distribution (RTD) tests in the later section (4.4). For example, the module with spacer-knitted fibers would facilitate a meandering fluid flow, thereby achieving a well-mixed condition. Moreover, secondary flows might be induced simultaneously to achieve more efficient heat and mass transfer.

Experiments were also conducted to investigate the effect of the lumen-side resistance by varying the recirculating permeate flow velocity (Re_p). Fig. 7 plots the permeation flux as a function of the permeate-side flow rate for six module configurations with Re_f =1901.3. A similar response to the increase of the permeate flow rate as the randomly packed module presented was observed for the five modified modules. Our previous work [12] indicated that the heat-transfer process could be enhanced by increasing the velocity to minimize the thermal boundary layer on the permeate side; i.e., when the temperature at the membrane surface approaches the temperature in the bulk permeate, the driving force for vapor transport through the membrane can be maximized. Moreover, an early onset of the steady state was observed at $Re_p<200$. The possible reason may be due to the increased transverse vapor flux that helped break down the laminar boundary layer, thus greatly enhancing the mixing on the membrane surface and facilitating the heat transfer at the permeate side. In addition, the four modified configurations show 28 to 39% flux enhancement compared to that of the with structured-straight module and a more significant improvement (110 to 127%) over the conventional randomly packed module after reaching a steady state (attainable fluxes). This is probably due to the enhanced heat transfer at the feed sides of those improved geometries, leading to a higher transmembrane vapor flux and consequently more efficient heat transfer at the permeate side.

4.4 Residence-time distribution (RTD) tests

In the RTD tests, when the sodium chloride solution was injected into the module at the feed inlet, it took time to travel through the whole system before reaching and being detected by the conductivity analyzer located at the feed outlet. The theoretical residence time, based on a plug flow vessel of the same actual volume ($V_{housing}$-V_{fibers}), was calculated to be approximately 7.2 seconds from the injection point to the detector with a flowrate of 2.1−2.4 $L \cdot min^{-1}$ and a connecting tubing length of approximately 500 mm. The tracer responses for different modules are shown in Fig. 8, which plots the concentration of the tracer in the effluent stream as a function of time. To view the experimentally determined *C(t)* curves more clearly, Fig. 8 depicts only the first 20 seconds of each module test. The solid lines and dots represent the experimental data, while the dashed lines are the Gaussian distribution curves (normalized distribution) that have symmetric shapes to simplify the probability prediction. For further comparison the average values of mean residence time t_m and the dimensionless variance σ_θ for each module are summarized in Table 2.

It can be seen from Fig. 8 that the curves of the randomly packed and structured-straight modules have double peaks that imply the existence of parallel flow paths or channeling in the modules [37]. Also, the relatively early peaks accompanied the occurrence of long tails on the right of the curves, implying that these two modules could be subjected to stagnant backwaters (local dead zone effects). The summary in Table 2 shows that their RTD curves have relatively wider dispersions (0.263 & 0.115) than the other modules.

Several researchers [35, 37, 42, 43] have stated that the variance is an important metric to evaluate the flow distribution. A smaller variance indicates a narrower RTD curve dispersion and a more ideal flow pattern. For example, the last three modules (Fig. 8) with curly, spacer-knitted and spacer-wrapped fibers show similar *C(t)* curves with a relatively spiked and asymmetric shape that indicate a reasonably uniform flow distribution, which is consistent with their small variances (lower than 10%, Table 2) indicating narrow curves. Although these three modules have relatively larger mean residence times t_m, which deviates from the plug flow behavior, they showed higher fluxes and enhanced performance in hydrodynamic investigations when compared to the other configurations. This may be due to their more complicated flow paths caused by the modified geometries that promote more even flow distribution and induce secondary flows to greatly enhance the mass/heat transfer between the hot feed and cold permeate. In addition, a direct comparison of the variance is illustrated in the histogram in Fig. 9 that shows a plot of dimensionless variance for the various module configurations. Interestingly, the overall RTD results correlate with the module performance.

4.5 Temperature-Polarization coefficient (TPC) and heat-loss assessment

A series of pure water tests were performed in the laminar flow regime to determine the corresponding heat-transfer coefficients and TPC for the various module configurations. The unknown parameters h and C were obtained based on the known operating parameters and membrane properties by plotting $\frac{\Delta T}{N\gamma}$ vs. $\frac{1}{dP/dT}$, as shown in Fig. 10.

Based on these plots, the heat transfer coefficient h was found to be from 943

W·m^{-2}·K^{-1} for the module with randomly packed fibers to 2300 W·m^{-2}·K^{-1} at T_m=333K for the module with curly fibers, which is consistent with its performance evaluation results. Also, the TPC and ratio of the conductive heat loss to the overall heat flux q_c/q for each configuration are shown in Figs. 11 & 12 as functions of the membrane temperature T_m, respectively. It can be seen that both the TPC and q_c/q decrease with increasing membrane temperature T_m. The TPC decreases because the higher fluxes generated by the higher vapor pressure gradient of dP/dT [(Eq. (2)] result in an increase in the effective membrane heat transfer coefficient H [(Eq. (3)]. Comparing the various designs (Fig. 11) the module with curly fibers shows the least temperature polarization under the same operating conditions (e.g., $\text{TPC} > 0.8$ at T_m=303K and 0.65 at 333K), followed by the module with central tubing and spacer-knitted fibers; while the modules with structured-straight and randomly packed fibers display higher vulnerability to the temperature-polarization effect. This again underscores the enhanced driving force and improved performance by the module with curly fibers. However, it is noted that the module with spacer-knitted module has a slightly lower TPC. This may be due to the more complicated layout and insertion of spacers leading to possibly lower thermal efficiency. Overall, compared to the TPC range (0.4−0.7) achieved by a typical MD system with satisfactory module performance [8], the current results are encouraging.

The ratio of the conductive heat loss to total heat flux, q_c/q, also decreases with increasing membrane temperature (Fig. 12), because q_c has linear relationship with the temperature difference $\left(T_{fm} - T_{pm}\right)$ while the evaporation heat q_e shows an exponentially increasing trend [Eq. (3)]. Interestingly, the module with curly fibers loses a larger portion of heat to conduction (e.g., 55% at T_m=30°C and 23% at 333 K), which is explained by a higher TPC and hence higher transmembrane temperature differences (driving force). Therefore, a trade-off exists between the TPC and the ratio of conductive heat loss to the total heat flux for module performance. However, it has been widely reported that the ratio of conductive heat loss to overall heat flux across the membrane is from 20% to 50% in a typical MD unit [8]. Thus, the conductive heat-loss levels of the best performing modules are still acceptable for the range of operating temperatures studied here. For example, the module with curly fibers had a $\mathrm{TPC} = 0.65$ and $q_c / q = 23\%$ at $T_m = 333\mathrm{K}$.

Based on the above results, a summary is given in Table 3 to provide an overall comparison for all configurations. In general, the modules with undulating membrane surface (e.g., curly and spacer-knitted fibers) show advantages by achieving higher vapor permeability and mitigating TP effect with reasonably lower energy losses; this is mainly due to the enhanced shell-side hydrodynamics induced by altered fiber geometries and relatively uniform shell-side flow distribution.

5. Conclusions

In this study, five types of novel hollow fiber module configurations were designed and constructed for the DCMD process. Their module performances were evaluated based on permeation flux experiments, fluid dynamics investigation, and tracer-response tests as well as process heat-transfer analysis.

- Experiments reveal that the novel module designs are able to enhance permeation flux up to 90% as compared to the conventional module, and the modules with curly and spacer-knitted fibers had the best performance.

- The fluid dynamic studies show that the performance of all modified configurations except the structured-straight module are independent to the feed flow velocity, and the modified fiber geometries with undulating membrane surface can achieve up to three-fold flux enhancement in the laminar flow regime.

- The sodium chloride tracer response technique is able to reveal the shell-side flow pattern and distribution for various designs. Improved fiber geometries or arrangements can provide a better flow distribution , thus much lower pumping energy cost and higher thermal efficiency could be accomplished.

- The heat transfer analysis underscores the advantage of the modules with undulating membrane surface for mitigating TP. Although a trade-off exists between the TPC and conductive heat loss, all modified modules showed acceptable heat loss within the range of operating temperatures.

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Nomenclature

A	Effective membrane area, m^2
C	Mass-transfer coefficient or membrane-distillation coefficient, $kg \cdot m^{-2} \cdot h^{-1} \cdot kPa^{-1}$
$C(t)$	Temporal tracer concentration at the effluent, $mol \cdot m^{-3}$
c_0	Pulse injection tracer concentration at the feed entrance, $mol \cdot m^{-3}$
d_o	Outer diameter of the hollow fiber, mm
d_s	Housing diameter of the module, mm
E_t	Tensile modulus, MPa
H	Effective heat-transfer coefficient based on the temperature difference across the entire membrane, $W \cdot m^{-2} \cdot K^{-1}$
h	Overall heat-transfer coefficient $\equiv \frac{1}{h_f} + \frac{1}{h_p}$, $W \cdot m^{-2} \cdot K^{-1}$
h_f	Feed-side local heat-transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
h_p	Permeate-side local heat-transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
k_m	Thermal conductivity of membrane, $W \cdot m^{-1} \cdot K^{-1}$
L	Effective fiber length, mm
M	Molecular weight of water, $g \cdot mol^{-1}$
m	Total amount of tracer, mol
n	Number f fibers
N	Vapor flux, $kg \cdot m^{-2} \cdot h^{-1}$

P	Vapor pressure of the bulk streams, kPa
q	Total heat flux, $W \cdot m^{-2}$
q_c	Conductive heat loss through the membrane, $W \cdot m^{-2}$
q_v	Latent heat flux, $W \cdot m^{-2}$
Q_f	Feed flow rate, L min^{-1}
Q_p	Permeate flow rate, L min^{-1}
Q_0	Influent flow rate in tracer study, $m^3 \cdot s^{-1}$
R	Gas constant, 8.314 $J \cdot K^{-1}$
Re	Reynolds number, $\frac{d_h v \rho}{\mu}$
r_{max}	Maximum pore size, μm
r_{mean}	Mean pore size, μm
T_f	Bulk temperature of the feed, K
T_{fm}	Temperature at the membrane surface on the feed side, K
T_m	Membrane temperature, K
T_p	Bulk temperature of the permeate, K
T_{pm}	Temperature at the membrane surface on the permeate side, K
ΔT	Bulk temperature difference, K
t	Time, s
t_m	Mean residence time, s
$\bar{t}$	Theoretical residence time of the vessel V/Q_0, s
V	Volume of the vessel, m^3

v_f	Recirculated feed velocity, m·s^{-1}
v_p	Recirculated permeate velocity, m·s^{-1}

Greek letters

ε	Membrane porosity, %
ϕ	Module packing density, %
τ	Temperature-polarization coefficient (TPC)
σ^2	Variance, s^2
$\sigma_\theta{}^2$	Dimensionless variance
θ	Dimensionless time
δ_b	Strain at fiber breakage, %
δ_m	Membrane thickness, μm
γ	latent heat-of-vaporization, J·kg^{-1}
ρ	Density of water, kg·m^{-3}
μ	Viscosity of water, Pa·s

Subscripts

f	Feed
p	Permeate

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